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A Review of Computer Evacuation Models and Their Data Needs

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16. Abstract

This document reviews the history and current status of computer models of the evacuation of an airliner cabin. Basic concepts upon which evacuation models are based are discussed, followed by a review of the Civil Aeromedical Institute's efforts during the 1970s. A comparison is made of the three models available today (GA Model, AIREVAC, and EXODUS). The report then reviews parameters common to all models, and discusses literature available as a basis for these parameters. Finally, the report briefly discusses validation exercises for evacuation models.

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Introduction

The situation found in passenger carrying aircraft may be a fire safety official's "worst nightmare." Potentially hundreds of passengers are closely seated in a long, narrow aluminum tube, surrounded by tens of thousands of gallons of highly flammable jet fuel. Should a fire begin as a result of some mishap, it is essential that all of these people evacuate the aircraft in the shortest possible time. Indeed, in most major aircraft accidents, all of the cabin occupants are alive at the moment that the airplane stops, but perish while trying to escape from the fire that follows. To ensure that passengers will survive an aircraft accident, the Federal Aviation Administration (FAA) requires manufacturers and operators of airliners to meet a number of design and performance standards related to cabin evacuation. Among the most controversial of these regulations is what is commonly called The 90 Second Rule (23). This regulation requires that a manufacturer demonstrate that an aircraft cabin can be safely evacuated in less than 90 seconds with half of the usable exits blocked, in darkness, and with a defined mix of gender and age among the simulated passengers. These demonstration tests are expensive to run, and are ethically questionable because of the very real possibility of some of the test subjects being injured in a test.

Given that safe evacuation is so critical to surviving an aircraft accident, and that showing compliance with the 90 second rule can be so burdensome, a computer simulation of the evacuation of an aircraft cabin is needed. A proven, validated computerized simulation tool could address several needs. As an accident reconstruction tool, such a simulation can provide insight into why some passengers perish while others survive, and how the design of the cabin might be modified to improve survivability. Aircraft designers would have a tool to make evacuation issues a consideration early in the design cycle—when changes are easily made. The FAA would have a tool available to assist in analyzing evacuation issues that confront the Agency.

Modeling Fundamentals

Evacuation models tend to be of two categories, network models, and queuing models (1). Virtually all models of aircraft evacuation are queuing models, as are many building evacuation models. Network models have been used to simulate building evacuations (1), a prominent example being EVACNET+, developed by the National Institute for Standards and Testing (NIST, formerly the Bureau of Standards). Network models develop paths between people and exits, and then use graph theory and combinatorial analysis to simulate the resulting evacuation. For a variety of reasons, aircraft evacuation simulations have been queuing models, rather than network models.

Whenever the current demand for a service (such as exiting an aircraft) exceeds the current capacity to provide a service, a queue (i.e., a line) results(1). Queuing theory is the body of knowledge that describes the dynamics of waiting lines. Mathematically, a queuing situation is a stochastic process in that it develops over time, and obeys the laws of probability. Thus, cabin evacuation models may be considered to be simulations of the formation and processing of lines at aircraft exits during emergencies.

Because queuing is a stochastic process, it is necessary to introduce a randomizer into the simulation. Common, non-computer related randomizers include items such as the throw of dice, or a deck of playing cards. With computers, mathematical routines generate a series of random numbers that are then used in decisions in the simulation. For example, assume that there is a 70% chance of moving from one section of an aircraft cabin to another. A random number between 0 and 1 is generated, and if that number is less than or equal to 0.7, then the simulated passenger moves. If the number is greater than 0.7, the simulated passenger does not move. Random number generators may have different probability distributions, but for evacuation models usually generate a uniform distribution. Random number generators typically need a starting value to calculate the random

series. This starting value is referred to as the seed. An identical series of random numbers is generated if the same seed is used. Some simulations allow the user to specify a seed, or the user can specify that the simulation generates a random starting value. A frequent source for a random starting value is the current date and time as read from the computer's clock. If different seeds are used, differing results of a simulation might be expected, and most aircraft cabin evacuation simulations allow the user to run a series of simulations with identical configurations, but using different seeds. The mean value of the results of these simulations is then studied.

We have defined a stochastic process as an event occurring over time and following the laws of probability. The use of random number generators allows a mechanism for introducing the laws of probability, but a means of simulating the element of time is also necessary. This factor is introduced through a simulation clock that begins counting at time 0 in a simulation, and continues until the simulation is completed. Each fraction of a second that 1 cycle of the simulation clock represents is referred to as 1 clock tick. Put too few clock ticks into a second, and you miss important details, resulting in the model being unable to accurately simulate the situation. Put too many clock ticks in, and the computational load (i.e., speed with which the simulation runs; size and expense of the necessary computer) increases without any added realism. Consider two extreme cases. If one clock tick is 90 seconds, you go from everyone seated to an empty aircraft without understanding the dynamics in between. If one clock tick is 1 millisecond (one thousandth of a second), you have to do 90,000 cycles for a 90 second simulation, yet, the difference in movement in 1 millisecond is, at best, undetectable. Selection of an appropriate clock speed is part of the "art" of computer modeling.

A typical aircraft evacuation model is a stochastic queuing model. Each passenger is represented and governed by a set of rules for their behavior that relate a probability generated by a random number generator to some probability of taking an action. A simulation clock runs the model. At each clock tick, the actions of each passenger are determined, based on the rules governing behavior, the probabilities generated by the random number generator, and the environment in which the passenger is located (e.g., locations and actions of other adjacent simulated passengers, presence of combustion toxins in the air, proximity and paths to exits, and whether blockages exist in the aisle). After each clock tick, passengers are moved to their new location, the cabin environment is updated, and the process is repeated until either everyone is evacuated or dead, or the simulation is stopped by the user.

Historical Development

The potential for a fire in a building also poses evacuation questions. Virtually every local government has an extensive set of building codes designed to reduce or eliminate both the possibility of a fire, and the risk of death and injury to people who might be in a building that catches fire. A primary consideration in these regulations is the safe evacuation of the building, leading to regulations concerning, the number, size, marking, and distribution of exits, and the maximum number of people who can safely occupy a room. Building designers have also been interested in computerized simulations of the evacuation process, for reasons similar to those of aircraft designers. This paper will not review computer simulations of the evacuation of a burning building, though the interested reader is referred to Watts (1).

One of the first efforts at computer modeling of an evacuating aircraft was pursued by the Civil Aeromedical Institute (CAMI) in the 1970s (2,3). These simulations depended on a special computer language developed by IBM called GPSS (General Purpose Simulation System), and required large mainframe computers to run. The simulations considered a number of features, such as passenger mix, seating and exit configuration, door opening delay, time on an escape slide, and slide capacity. The simulations were intended for study of certification tests, and not necessarily for accident reconstruction. As a result, the models did not simulate life-threatening factors, such as toxic combustion gas products, nor did they consider passenger behavior in a life-threatening situation. The model was used to simulate narrow-body, single-aisle aircraft (Boeing 720 in 124-and 234-passenger configurations), and wide-body, dual-aisle, aircraft (B-747, DC-10, and L-1011).

Type of Aircraft	Passenger Load	Certification Time (sec)	Average Simulated Time (sec)	Redirection
B-747	527	66.2	84.0	Yes
L-1011	356	101.1	93.5	No
L-1011	356	82.0	84.9	Yes
L-1011	411	89.7	79.6	Yes

TABLE 1 — Comparison of Simulation and Certification Evacuation Times (Garner, Chandler, and Cook, 1978)

Table 1 compares the evacuation times from certification trials and from the simulations conducted. Note the counter-intuitive result, found in both the simulation and the certification tests, of an L-1011 with a higher passenger load recording a faster evacuation time compared to an L-1011 with a lower passenger load. A further difference between these two tests is that the 356-passenger model used three Type A, and one Type I exits, while the 411-passenger model used four Type A exits. The last column, labeled Redirection, refers to a feature of the tests. If passengers are instructed to use a particular exit regardless of the queue, redirection is "No." If passengers may change the exit they use in an attempt to find the shortest line/fastest exit, then redirection is "Yes."

Some of the potential for computerized simulation of evacuation is revealed in Table 1. Note that with the L-1011 simulations, potential design changes (Type A versus Type I exits) were analyzed, as well as differing passenger loads.

Examination of Table 1 shows that the simulations both under- and over-predicted the times from the evacuation trials though the simulated times are comparable to the certification times. It should be noted that the certification trials represent a single test, while the simulations represent averages of as many as 20 repeats. It is unlikely that if a certification test were repeated the same evacuation time would be found again, and with only a single test the variation and standard deviation of these times are indeterminate. Garner, et. al., (3) concluded that their model could closely simulate actual evacuation times, and recommended that additional research be done to refine the inputs needed by their model.

This early work showed the potential of evacuation models, as well as revealed the limitations. There was very little research on which to base the modeling parameters needed, and yet this was identified by the study's authors as critically needed information. In addition, using the models required large mainframe computers, the situations studied were not easily changed without rewriting a GPSS program (and GPSS is not a widely known computer language), and the results of the simulations tended to be large printouts with many numbers, thus, not easily understood.

Review of Current Models

Today there are three different cabin evacuation models in development and use. These models, to be described in detail, are the Gourary Associates (GA) Model, developed by Barry Gourary under FAA sponsorship(4); AIREVAC, developed by James Schroeder under Air Transport Association of America sponsorship(5); and EXODUS (6), developed in England by Ed Galea. In the following discussion it is important to examine the guidance given to the model's developer when considering limitations of a model. Given enough time and money, virtually any model can be modified to add any capabilities that it lacks. In a

world of finite time and financial resources, the model's developer has made choices based on sponsor guidance, which result in the simulation's limitations.

GA Model

After the early modeling work at CAMI (2,3) an effort was initiated to build on the strengths, and correct some of the weaknesses identified in the previous effort. In 1987, Barry Gourary of Gourary Associates (GA) developed a new cabin evacuation model under Federal Aviation Administration (FAA) sponsorship (4). Guidance given to GA included that the model should run on then state-of-the-art personal computers, produce a graphical display of the results, run in near real time, and be flexible in terms of cabin arrangements and passenger characteristics without requiring a programmer to rewrite the simulation each time. Further, the sponsorship of this model development occurred under a government program known as the Small Business Innovative Research (SBIR) program. Central to the SBIR program is a requirement that the project produce a commercially viable product, in this case, a computer program that could be sold to interested users. Note that in 1987 a state-of-the-art personal computer was based on an Intel 80286 processor, a now outdated technology. The resulting model was used to reconstruct three actual aircraft accidents. A number of improvements were made after the initial released, with the most recent having been completed in late 1992 (4).

The GA model divides an aircraft cabin into a series of cells. Each cell is the length of one row, and the width of one seat and/or aisle. Each passenger is described by a number of parameters, such as their endurance or agility, and each passenger is assigned an exit to use. A cell may be occupied by at most 2 passengers, and with each tick of the simulation clock (3 ticks per simulated second) the passengers attempt to move to their assigned exit. Each passenger has a defined probability of moving from one cell to the next, and this probability is a function of their endurance, agility, and surroundings. In contrast to most other evacuation models, in the GA Model the speed at which passengers move is not a user-defined parameter, but is specified by the probability of moving from one cell to the next. Thus, a faster passenger has a higher probability of movement compared to a slower passenger. The movement probability is influenced by a factor that reduces the passenger's endurance (i.e., ability to live and move) with each tick of the clock. When the passenger's endurance drops below a threshold value, that passenger is considered a fatality. As the simulation runs, the user may specify that passengers are no longer required to use their assigned exit, rather, the passenger will use the closest available exit. It is also possible to simulate a flight attendant at an exit, thus, increasing the probability of someone successfully exiting during a clock tick. Only one exit in the aircraft at a time may have a simulated flight attendant stationed at that exit, though Gourary has suggested techniques to simulate flight attendants being stationed at several exits during a single clock tick (24).

The program produces a graphical display showing an overhead view of the seats, rows, exits, and occupants. Color coding differentiates dead passengers from those still capable of escaping. Without any specialized computer knowledge, the user may set characteristics of the cabin and passengers. The number of exits is fixed at 4 overwing exits, and main exit passageways at the front and rear of the cabin. However, fewer exits may be simulated by specifying an infinite time to open an exit. Only a single-aisle aircraft with at most 3 seats per row on each side of the aircraft may be simulated, i.e., wide-body, dual-aisle aircraft cannot be studied.

A user of the GA Model does not require any specialized computer knowledge, such knowledge of a programming language. Input to the program is performed with editors supplied with the model. The input files are stored in a non-standard file format, and only the editors supplied with the program can be used to enter and modify data. The software was written in MS Basic (24), though the source code for the program is not available. Options in terms of specifying printers, video drivers, etc., are, at best, limited.

The model includes a crude toxic environment simulation to represent the influence of combustion products from a fire. The user may specify a maximum of two zones with harmful fire and smoke environ-

ments within the cabin. For each zone, at some user defined time in the simulation, the environment in each zone goes from completely non-toxic, to some degree of life impairing. The toxicity of the cabin environment is different in each zone, however, the life impairment function cannot be based on a function of time, and there is no transition between zones. The toxicity of the environment is specified by a numeric value. This value is an additional decrement per simulation clock tick in each passenger's endurance. Little guidance is available for determining these values.

When the program was originally developed, problems were noted with blocked passenger flows. Two situations in which this occurred were when a cell on the path to an exit was blocked by two fatalities, and when two groups of passengers going in opposite directions (e.g., one group headed for the forward exit, the second group headed for the rear exit) met at the same cell. In the situation with two fatalities in a cell, it was no longer possible for other surviving passengers to pass through. While this is not an impossible situation, there is a distinct possibility that in a real situation, a still surviving passenger seeking to exit would get around the fatalities blocking the path. Since the original release, the GA model has been modified to simulate the possibility of passage, albeit with a reduced probability (implying a slower speed) through a blocked cell. The problem with opposed flows would result in the flow halting while each side tried to pass the other. While the question of what would happen in a real situation is unresolved (would not people in one of the two flows think that the other people knew where they were going?), the program has been modified to introduce a probability to each flow of passing the other.

As examples and validation of the GA Model, Gourary reconstructed three accidents, and modeled the aircraft used in some of these accidents in simulated certification tests (i.e., without the environmental toxins being turned on)(4). The three accidents reconstructed were 1) United DC-8 with 114 passengers, Denver, Colorado, July 1961; 2) United B-727, Salt Lake City, November 1965 with 85 passengers on board; 3) Texas International DC-9, Denver, Colorado, November 1976 with 81 passengers. The first two accidents were simulated because exquisitely detailed accident investigations were available in (8). The third case was selected as being an example of where the GA Model could be applied. In performing these simulations Gourary (4) noted the limitations of the data upon which to base modeling parameters, and in the case of the Texas International DC-9, the lack of information from the accident investigation.

AIREVAC Model

AIREVAC was developed by James Schroeder, originally of the Southwest Research Institute, under sponsorship of the Air Transport Association (ATA) of America (5, 17). AIREVAC was developed to simulate a certification test, and not for accident reconstruction. In particular, AIREVAC was developed to study the impact on aircraft emergency cabin evacuations of transporting disabled passengers. While this was the immediate goal, Schroeder sought to develop a model with potentially wider applications.

Within the guidelines provided by ATA, Schroeder developed a model of a certification evacuation test (i.e., no simulated fire or other environmental assaults) of a B-727-200 aircraft. The model can simulate any number of passengers up to the capacity of the plane, but cannot be used without reprogramming to simulate any other type of aircraft, either a wide-body, dual-aisle or a narrow-body, single-aisle aircraft other than a B-727. However, the model can be reprogrammed to simulate other types and configurations of aircraft, though this requires a user knowledgeable of Simscript, the computer language used by AIREVAC.

Simscript is a specialized, relatively unknown computer language used for simulating systems. AIREVAC was developed and runs on a SUN Workstation, though work is in progress to port it to an Intel 80x86-based machine. The program runs much more slowly than real time, and to simulate 90 seconds of an evacuation of a full plane takes several hours. The smaller the passenger load, the faster the simulation runs. The simulation clock runs at 5 ticks per second.

Schroeder's model uses many of the parameters commonly required by an evacuation model, such as number of passengers, their location, and their speed of movement. However, AIREVAC features a de-

tailed set of psycho-social parameters describing someone's reaction to being in an evacuation. A passenger is described by specifying these characteristics (e.g., frustration index, dominance/submission, knowledge of aircraft exits and routes). The number of parameters, and their associated values represent a prohibitive impediment to creating a data set describing all of the individuals on a full plane. To solve this problem, Schroeder derived mean values, and the distribution around these mean values for each parameter needed. AIREVAC features a randomizer that creates as many passengers as needed for a simulation, with each passenger representing a unique, random collection of the required parameters. While a user can specify any of the values, the more common situation would be to depend on the randomizer. In this manner, the program creates a representative sample of the American population.

The initial goal of the AIREVAC was to simulate a certification test. As a result, the model lacks capabilities needed for accident reconstruction, such as simulation of the debilitating influence of toxic smoke. In addition to the physiological debilitation, a model such as AIREVAC with detailed psycho-social simulation capability, needs additional parameters to describe someone's reaction to an emergency. For example, parameters describing someone's panic behavior, bonding of families, etc., have been suggested as being important in an emergency, and not necessarily important in a certification test. Thus, for AIREVAC to perform accident reconstruction it not only needs a means to simulate the toxic environment found in an accident, but also to simulate people's behavior in that situation.

EXODUS

EXODUS was developed in conjunction with computational fire dynamics (CFD) modeling research conducted at the University of Greenwich in England. CFD attempts to simulate the growth and spread of a fire, and to predict the combustion products and temperatures that result from a fire. In conjunction with this research, Ed Galea developed EXODUS (6) to simulate emergency evacuation of an aircraft. Galea has proposed and used EXODUS to simulate evacuations in other situations that find large numbers of people in an enclosed space, in close proximity to each other, with a limited number of exits, and exposed to a fire. In addition to aircraft, the model has been and/or can be used to simulate evacuation from trains, theaters, cinemas, and lecture halls. EXODUS is a separate program from the CFD model, but it can accept information calculated by a CFD model about the cabin environment. EXODUS can also accept information empirical data collected from fire tests. Because EXODUS can accept detailed cabin environmental data it has the ability to perform accident reconstructions that feature sophisticated simulation of the generation and absorption of toxic environmental elements from the fire (such as carbon monoxide, hydrogen cyanide, heat, etc.). EXODUS has been used to simulate both wide-body, dual-aisle and narrow-body, single-aisle aircraft. The simulation can be used for certification tests and for accident reconstructions.

EXODUS is an expert system-based simulation, and was developed in a software environment developed by G2(7). To run G2, and by extension EXODUS, requires a SUN SPARC-1 workstation, though work is in progress to place EXODUS onto an INTEL 80486 based or better platform. While EXODUS in conjunction with a CFD simulation is very detailed, it requires a level of computer knowledge, and a sufficiently powerful computer that puts it out of the reach of all but the most sophisticated users. However, by itself, with data from a previously run CFD model or an experiment, EXODUS runs in a few minutes.

EXODUS features an extensive graphical display of the simulation's progress and results, detailed information on how much of the environmental toxins were absorbed by each passenger during the test, and the time for each passenger to exit the aircraft, or until their death. EXODUS is composed of five interacting components which together describe the evacuation process of a cabin. These five components are:

Movement model controls the physical movement of individual passengers, or supervises the waiting period if movement is not possible.

Behavior model determines an individual's response to the current situation based on that passenger's personal attributes, and then passes the decision to the movement model. In the current implementation, all passengers head for the nearest serviceable or assigned exit.

Passenger model describes an individual in terms of 22 attributes and variables such as name, gender, age, movement speed, dead/alive, etc. Some attributes are fixed and unchanging, while others change in response to information from other sub models.

Hazard model describes the atmospheric and physical environment. It controls fire hazards such as heat, and combustion product toxins, as well as the opening and closing of exits.

Toxicity model determines the effects on an individual exposed to the toxins calculated and distributed by the hazard model. The toxicity model communicates with the behavior model, and in turn the movement model, to simulate the reduced ability to escape the cabin fire as it progresses.

EXODUS has been demonstrated in a hypothetical wide-body, dual-aisle aircraft under both simulated fire, and certification demonstration types of tests(6). The model has also been used to reconstruct the British Airtours B-737 aborted takeoff and fire at Manchester Airport in 1985 (9).

To demonstrate the validity of EXODUS, Galea (6) simulated a series of controlled evacuation tests from a Trident Three aircraft conducted by Helen Muir at the Cranfield Institute of Technology (10). Muir conducted both orderly evacuations, and used a unique financial incentive to simulate panic among passengers. Galea simulated both orderly runs, and in some simulations, allowed the simulated passengers to climb over seat backs in an attempt to exit more quickly. Galea's modeling parameters were based on his initial "guesses" of the parameters needed, yet predicted similar trends to those found by Muir. While the trends predicted by the simulation matched those found in the tests, the model predicted that the cabin would be evacuated in less time than recorded in the tests (i.e., the model predicts a faster evacuation than experienced). These results must be considered within the context that Galea had little basis for and limited opportunity to modify the parameters that he used.

Data Needs and Sources

Any simulation depends on parameters that describe how a system responds to some event. This is true whether the simulation is of a piece of steel being bent, or a human passenger escaping an aircraft fire. The simulation can never be any better than the parameters that describe the system, and parameters that characterize human response can be some of the most difficult to obtain. All cabin evacuation modeling efforts (2, 3, 4, 5, 6) have identified limitations in the sources and quality of data upon which to base modeling parameters as a primary impediment to the accuracy and application of the models.

While each model tends to have unique parameter needs, there are a number of parameter needs common to all models. For example, the GA Model (4) seeks a single parameter to quantify an individual's strength and ability to tolerate fire generated toxins. The GPSS models (2,3) and AIREVAC (5) have no such parameter, in part because they are not, as developed, suitable for accident reconstruction. In contrast, all models (2-6) depend on information about flow rates in aisles and through exits.

This section will describe some of the parameters common to all evacuation models, and identify existing sources of information usable as a basis for modeling parameters. The reader is referred to the work of Schroeder (17) in the early stages of the development of AIREVAC. In (17) Schroeder has an extensive literature review, including his conclusions about the applicability to cabin evacuation modeling of the data in the references he found. This literature review included information relevant to accident reconstruction modeling where combustion product toxicology and physiological responses are important.

Central to all models is the issue of passenger flow rates, and all models need information about how fast people move in aisles, move through exits and onto slides, and how quickly people will move from a row into the main aisle. Related parameters include how long it takes people to undo their seat belt, how long to begin to move purposefully towards an exit, and how long it takes to open aircraft exits and inflate slides. It can be assumed that through much of the simulation a queue (i.e., a line) will exist either at an exit, or at some other point in the cabin. When a

queue exists, the model must simulate the behavior of people in deciding who goes first. The models differ in their approaches to this type of behavior. While the models differ, and as a result have different data needs, there are common data needs even though the manner in which this information is used may differ. Parameters affecting flow rates are not independent of parameters affecting queuing. If a slow moving passenger is at the front of a line, no one in that line can move faster than that slowest passenger. However, if a faster passenger who is behind becomes impatient, and has the desire and physical ability to cut the line, that faster passenger can get out before the slower passenger.

The models vary in how they simulate strength, agility, and resistance to the toxic effects of smoke. Each model has a unique approach to simulating the cabin environment, ranging from AIREVAC that cannot simulate an environment other than clear, clean air, to EXODUS that can be run with a very sophisticated computational fire dynamics model to accurately predict the combustion product toxins in the atmosphere at each individual location in the cabin, and how much of the toxins are absorbed over time as a passenger moves through the cabin.

Research at CAMI has examined many aspects of evacuation performance from passenger aircraft (8, 11-16). The Blethrow report (15) is particularly useful for quantifying the agility of an escaping passenger, and how this agility is reduced by physical impairments such as blindness, obesity, or old age. Data relating to evacuation rates through doors and down slides may also be obtained from airframe manufacturer's research (18-20). All of the evacuation models allow for the specification of passenger age, gender, and indications of mobility impairments. While age and gender are stored, there is no direct relationship in any of the models between these factors and the passenger's speed, agility, or endurance. Many evacuation studies have identified gender as a factor that influences a passenger's speed and agility, but there are no widely agreed upon factors to quantify these influences. A recent evacuation study at CAMI, in which age was a controlled variable (21), found that a younger group of test subjects evacuated the cabin over 25% faster than an older group in the same cabin configuration. Other factors that may influence a passenger's speed, such as bonding of husband and wife, or parent and child, have been identified by model developers, but never quantified.

Data for use in quantifying the time needed by a passenger to perceive that the plane has stopped, unfasten the seat belt, get out of the seat, and begin to move purposefully to an exit are not generally available, but are essential parameters for any simulation. Times to prepare and open doors, and make evacuation slides ready for use, are other factors not generally available. These parameters are particularly important in accident reconstructions, yet are virtually impossible to determine from accident investigations. If the plane is on fire, who is going to time how long it takes to get the door open rather than trying to assist in the rescue?

Parameters needed to model the toxic effects of smoke and heat from a cabin fire are difficult to obtain. A complicating factor is that in an aircraft fire, time to incapacitation may be more important than is time to death. In general, incapacitation occurs long before death does, but death is likely in an aircraft fire if a passenger is incapacitated. EXODUS (6) uses, and AIREVAC (17) noted for future application, the work of Purser (22) in defining fractional doses of typical aircraft fire toxins, and the threat to life that these represent. Using data from a detailed computational fire dynamics model, EXODUS can provide a very good simulation of the combustion products presented over time to passengers as they move about the cabin. Computational fire dynamics modeling is a very sophisticated, specialized, and complicated subject far beyond the scope of this paper to discuss. The interested reader is referred to (6) as a starting point for more information.

The psycho-social reaction of passengers in a fire, for use in an accident reconstruction, may differ from the behavior seen in a certification test. Muir (10) has studied differences in cabin evacuations between a certification type of test, and evacuation tests in which a simulated panic occurred. Schroeder (17), as part of his work developing AIREVAC, considered how to model passenger behavior in a fire.

Validation of Models

For any model to be used with confidence, the accuracy of the model must be validated. Of the models discussed in this paper, validation efforts have ranged from matching certification tests, as was done with the GPSS models developed at CAMI in the 1970s, to accident reconstructions, as attempted by Gourary. The validation work of Galea with EXODUS (6) may be the most extensive including an accident reconstruction (the British Airtours Manchester accident), a hypothetical case (a wide body aircraft), and replicating carefully controlled experimental evacuation tests run by Muir. In all cases, the simulation results are based on a sample of runs to introduce the inherent variability in any stochastic process, yet the results are compared to a single test (or accident) from an equally stochastic process. That there will be some variation is unavoidable. The general conclusion of all model development activities has been that the models match the trends seen in the real world, but that differences do exist. These differences are generally attributed to limited information for use in describing the system to the model.

Accident reconstructions are a more formidable validation exercise. In addition to the variability from being a stochastic system, there are a great many unknowns in an accident. Neglecting details, such as how the fire starts, and how quickly it spreads, it is frequently difficult or impossible to obtain such basic information as the age, gender, weight, physical condition, and/or actual seated location of the passengers in the plane. Other critical information, such as the time for door opening and slide inflation is even more difficult to obtain. Thus, if an accident reconstruction is to be used as a validation basis, one cannot expect an exact match. General trends, such as the location and number of fatalities demonstrates the accuracy of the model. An interesting possibility with accident reconstructions is to study the influence of potential design changes (e.g., moving the location of an exit, or changing the type of exit and the resulting flow rate) on the number of fatalities resulting from the accident.

Data from certification type tests should be more easily available, have more available information (such as complete subject descriptions and seating locations), and less confounding factors, such as the spread of a fire. While this makes them more suitable in the early stages of a validation exercise, it also means that the model has not been validated to study real or potentially real accident situations. Perhaps the best validation exercise would be a set of carefully controlled evacuation tests with only a few experimental variables. Validation exercises such as these would include detailed information for use in the development of a model's parameter data set, and evaluation of the sensitivity of the model's results to various parameters. While toxic smoke cannot ethically be introduced into a cabin full of people, non-toxic theatrical smoke that obscures vision can be used in validation exercises.

SUMMARY

After an aircraft accident occurs, quick evacuation of the cabin may be the most important factor influencing survivability of the accident. The FAA has a variety of regulations regarding training, operation, and design of aircraft to ensure as fast a cabin evacuation as possible. In order to better understand factors that influence the evacuation process, to understand the evacuation process in accidents, and to provide guidance at an early stage in the design cycle of new aircraft, computerized simulations of an aircraft cabin's evacuation have been studied.

In the 1970s CAMI developed and used a computerized cabin evacuation model that required a large mainframe computer, and whose output was not easily interpreted. While the model did not exactly match certification trials of some current aircraft, the model held the promise that if all necessary parameters could be defined, computerized evacuation modeling could become a powerful tool in the design of safer aircraft. Today, there are three leading models in various stages of development.

In the mid-1980s CAMI sought to develop a new computer model that could run on an inexpensive personal computer in near real time, that would produce an easy-to-understand visual display, and that could be easily modified by a non-programmer. The GA Model, developed from this effort, is available today. While meeting the model development's origi-

nal goals, the model is limited by a crude cabin environment model, and by the inability to simulate a wide-body, dual-aisle aircraft.

The Air Transport Association sponsored the development of a cabin evacuation model, principally to assess the impact on evacuation performance of carrying mobility-impaired passengers. The resulting model, AIREVAC, has a detailed simulation of a passenger's psycho-social responses to an evacuation, but as presently constructed, it can only represent a single model of an aircraft, and cannot simulate a fire (i.e., it is not suitable for accident reconstruction, but only for certification tests).

EXODUS offers the ability to perform detailed simulations of the toxic effects of an aircraft fire. The simulation has already been used successfully to simulate a wide-body aircraft, a series of evacuation tests at the Cranfield Institute, and to reconstruct the 1985 Manchester, England, B-737 accident.

All models depend on parameters to describe the system being analyzed. Most evacuation model developers have noted the limitations on sources of data upon which to base needed parameter values, and attributed limitations in the accuracy of their models to these shortcomings in the available data. In this paper, many of the available sources of data were identified, and an even more complete description may be found in Schroeder (17). In the future when evacuation tests are planned, consideration should be given to obtaining data that will be useful in the determination of modeling parameters.

The validation of evacuation models can be based on three possible sources. The most challenging is to reconstruct accidents. Given the formidable nature of this method, exact agreement is not expected, only a general agreement in the location and number of fatalities can be expected. Simulation of certification tests is simpler, and certification tests may have more information available for the modeler. However, the best validation exercises will be evacuation tests designed explicitly to serve as validation tools for computer models.

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